Baryon exotic theoretical overview

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Outline :

1. Penta-quark components in the proton

Classical picture of the proton

Constituent Quarks

Parton Distributions
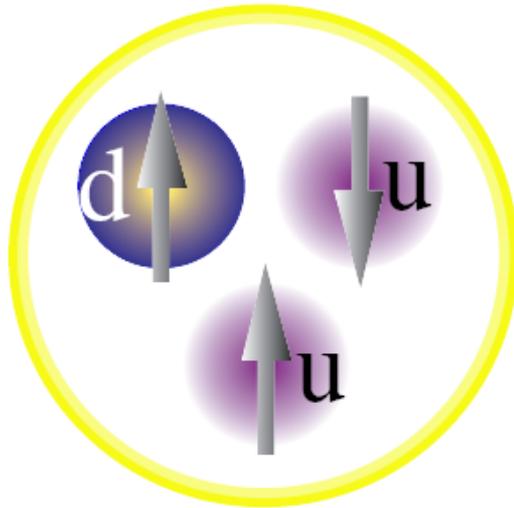
$(Q^2 = 0 \text{ GeV}^2)$
baryon octet
masses, magn. momenta
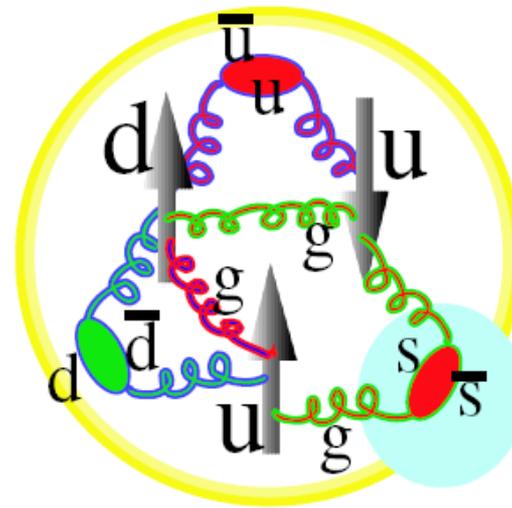
$(Q^2 > 1 \text{ GeV}^2)$
structure functions
momentum, spin

$$\overline{u}(x) = \overline{d}(x) , \quad \overline{s}(x) = s(x)$$

1964-1974

1974–1992

◆ 5-quark components in the proton

Flavor asymmetry of light quarks in the nucleon sea

Deep Inelastic Scattering (DIS) + Drell-Yan (DY) process

$$\rightarrow \quad \bar{d} - \bar{u} \sim 0.12 \quad \text{for a proton}$$

Garvey&Peng, Prog. Part. Nucl. Phys.47, 203 (2001)

Spin crisis for the proton

expt.: $\Delta u \in [0.82, 0.85],\ \Delta d \in [-0.45, -0.42],\ \text{and}\ \Delta s \in [-0.11, -0.08]$

QM: $\Delta u = 4/3,\qquad \Delta d = -1/3,\qquad \Delta s = 0$

Two schemes for $\bar{d} - \bar{u} \sim 0.12$ **&** **spin crisis**

Meson cloud picture: Thomas, Speth, Henley, Meissner, Miller, Weise, Oset, Brodsky, Ma, …

$| p > \sim | uud > + \varepsilon_1 | n\,(\,udd\,)\,\pi^+\,(\,\bar{d}u\,) >$

$\qquad\qquad + \varepsilon_2 | \Delta^{++}\,(\,uuu\,)\,\pi^-\,(\,\bar{u}d\,) > + \varepsilon' | \Lambda\,(uds)\,K^+\,(\,\bar{s}u\,) > \ldots$

Penta-quark picture : Riska, Zou, Zhu, …

$| p > \sim | uud > + \varepsilon_1 | [ud][ud]\,\bar{d} > + \varepsilon' | [ud][us]\,\bar{s} > + \ldots$
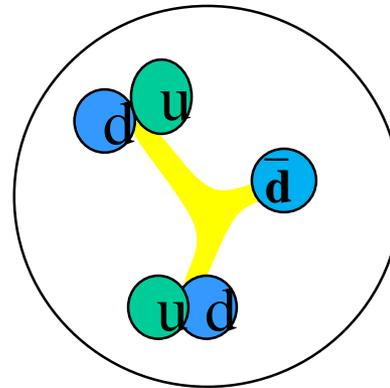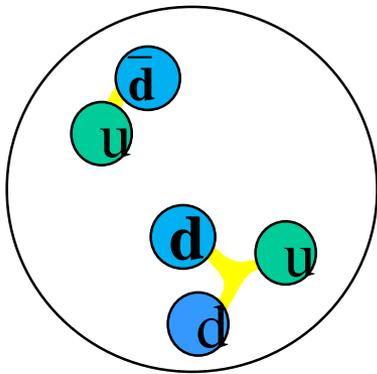
➔ **~ 30% 5-quark components in a proton**

2. Pentaquark states before LHCb P_c states

Fate of the first pentaquark predicted and observed:

1959: $\overline{K}N$ **molecule predicted by Dalitz-Tuan, PRL2, 425**

1961: $\Lambda(1405) \rightarrow \Sigma\pi$ **observed by Alston et al., PRL6, 698**

1964: **Quark model (uds) for** $\Lambda(1405)$ **– the lowest ½- baryon**

1995: $\overline{K}N$ **dynamically generated -- Kaiser et al., NPA954, 325**

2001: **2 pole structure by** $\overline{K}N$-$\Sigma\pi$ **-- Oller et al., PLB500, 263**

PDG2010: "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ —true 3-quark state or mere $\overline{K}N$ threshold effect?— unambiguously in favor of the first interpretation."

Fate of the last famous fading pentaquark $\theta^+(1540)$:

1997: $Z^+(1530)$ predicted by Diakonov et al., ZPA359, 305

2003: $\theta^+(1540) \rightarrow K^+n$ claimed by LEPS, PRL91, 012002

2003: $\bar{s}$ (ud)(ud) for $\theta(1540)$ by Jaffe&Wilczek, PRL91, 232003

2003: $\bar{s}$ ud)(ud) for $\theta(1540)$ by Karliner&Lipkin, PLB575, 249

2004:   supported by 10 expts $\rightarrow$ $\theta(1540)$ well-established by PDG

2004:   not supported by BESII, PRD70, 012004

2005:   not supported by many high stats experiments

2006:   removed from PDG

Note: $\theta^+(1540)$ is not supported by hadronic molecule model & chiral quark model by Huang, Zhang, Yu, Zou, PLB586(2004)69

While lacking expt constrains on models of compact pentaquarks, models for hadronic molecules are much better constrained.
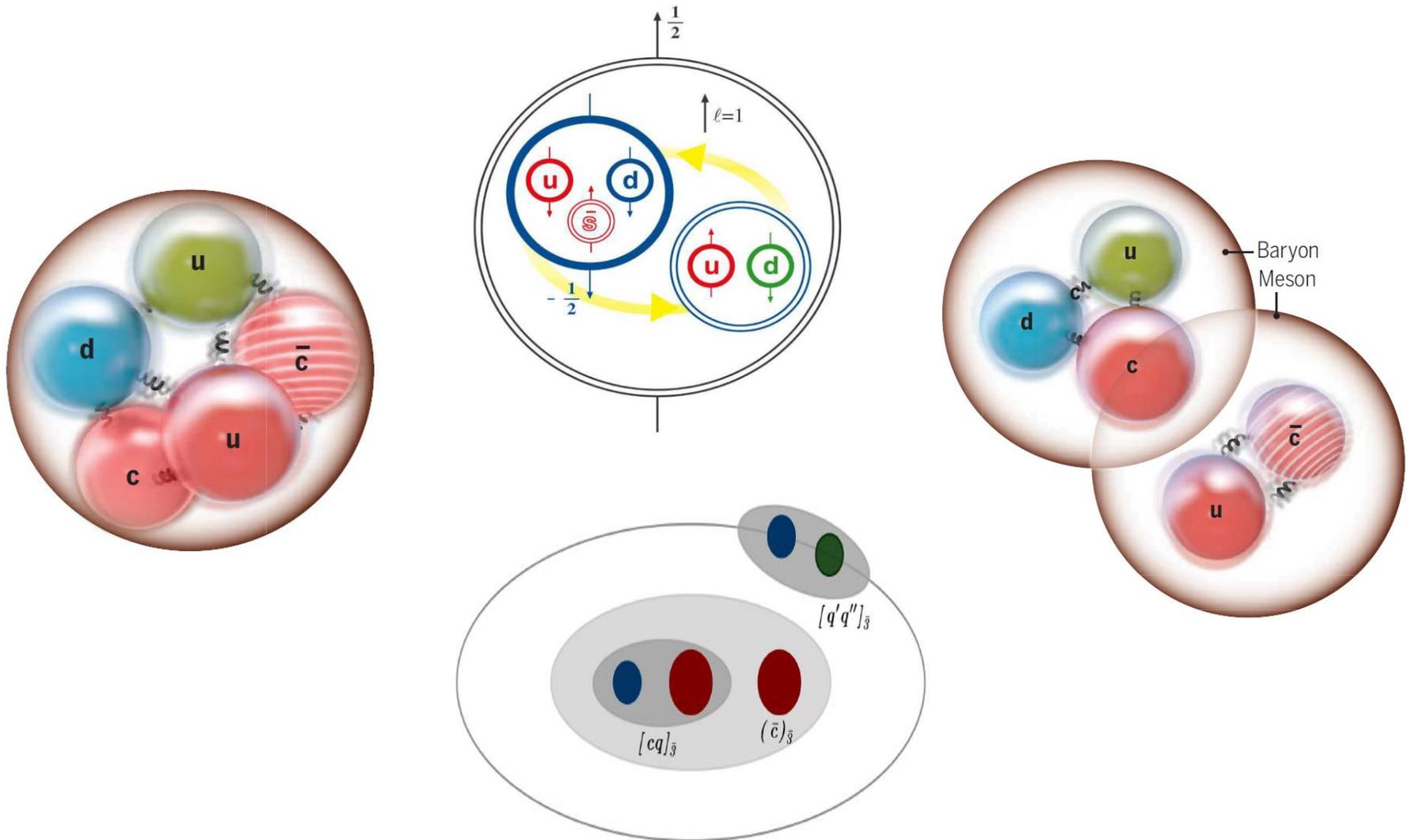
Similarity for ππ, πK and πN s-wave scattering phase shifts
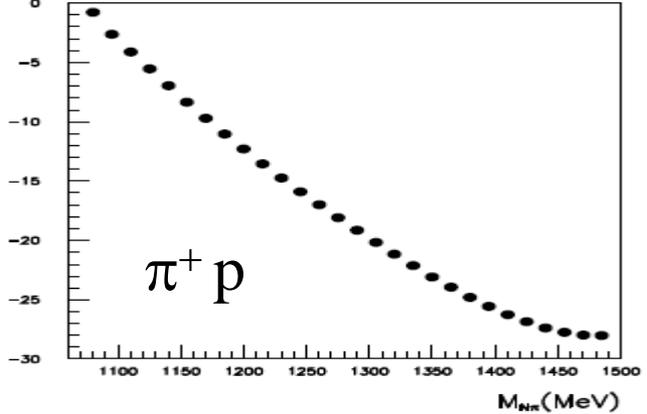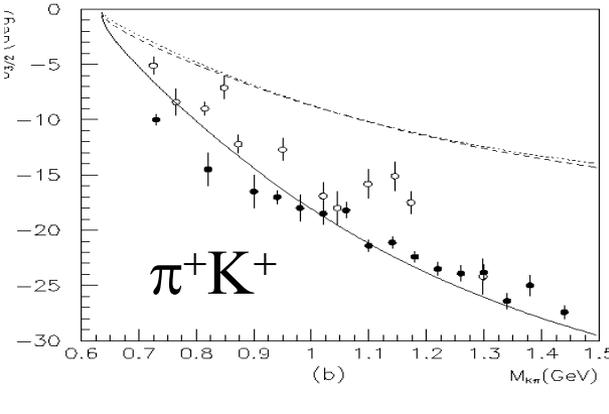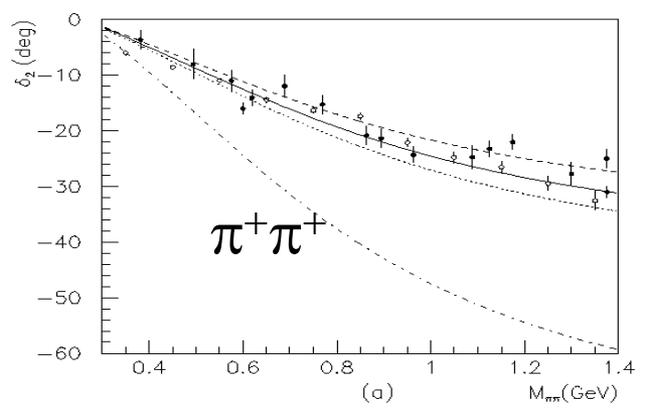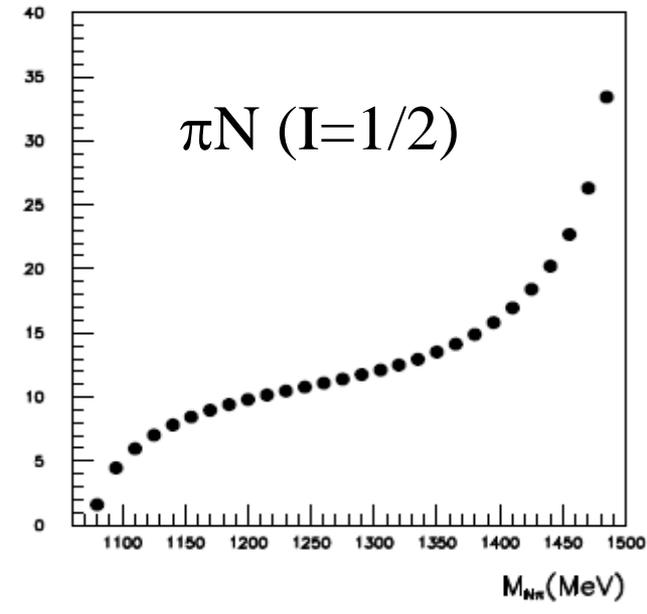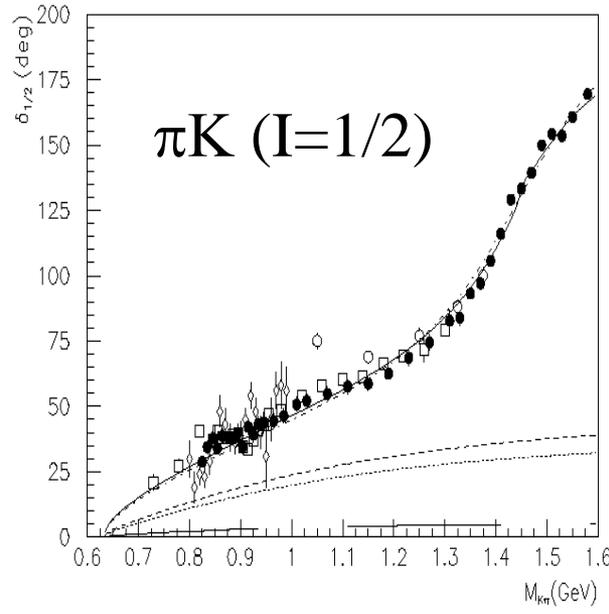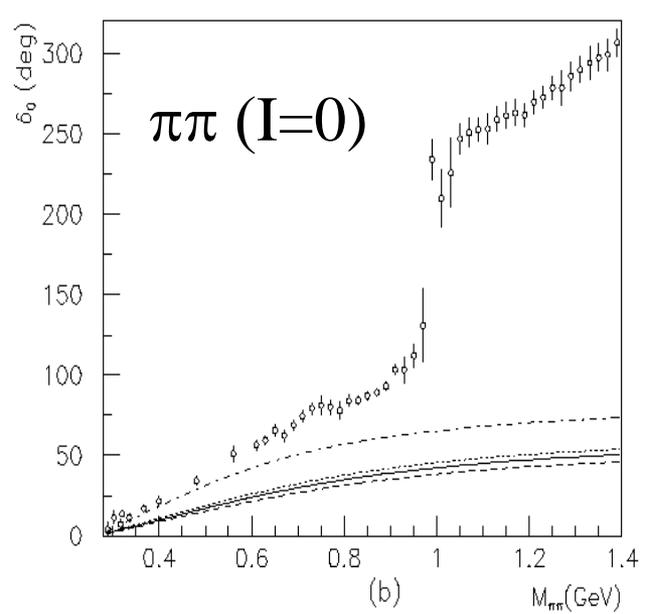
Important role by t-channel ρ exchange for all these processes
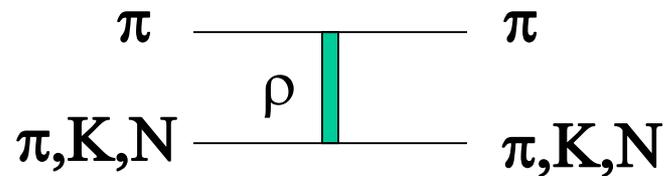
$\pi\pi$ πK & πN

$$K_\rho^{I=0} = -2 \, K_\rho^{I=2}, \qquad K_\rho^{I=1/2} = -2 \, K_\rho^{I=3/2}$$

D. Lohse, J.W. Durso, K. Holinde, J. Speth, Nucl.Phys.A516, 513 (1990)
B.S.Zou, D.V.Bugg, Phys. Rev. D50, 591 (1994)

An interesting paper by T.Hyodo, D.Jido, A.Hosaka, PRL 97 (2006) 192002
"Exotic hadrons in s-wave chiral dynamics"

	$\overline{K}N(I=0)$	$\overline{K}N(I=1)$	$KN(I=0)$	$KN(I=1)$
Phase shifts:	strong +	weaker +	weaker −	strong −
VMD :	$-V_\omega - 3V_\rho$	$-V_\omega + V_\rho$	$V_\omega - V_\rho$	$V_\omega + 3V_\rho$

Similarity between $\pi\Sigma$ - $\overline{K}N(I=0)$ and $\pi\pi$ - $\overline{K}K(I=0)$

dipole structure for $\Lambda(1405)$ $\leftarrow$ σ - $f_0(980)$

VMD – ChPT unitarized $\rightarrow$ N*(1535) as $K\Sigma$ bound state

Kaiser et al., PLB362(1995)23

A new direction to pin down pentaquark states :

Extension to hidden charm and beauty for baryons

N*(1535) $\bar{s}suud$ B.C.Liu, B.S.Zou, PRL96(2006)042002

N*(4260) $\bar{c}cuud$ J.J.Wu, R.Molina, E.Oset, B.S.Zou,
            Phys.Rev.Lett. 105 (2010) 232001

N*(11050) $\bar{b}buud$ J.J.Wu, L.Zhao, B.S.Zou, PLB709(2012)70

Λ*(1405) $\bar{q}quds$

Λ*(4210) $\bar{c}cuds$ J.J.Wu, R.Molina, E.Oset, B.S.Zou,
            Phys.Rev.Lett. 105 (2010) 232001

Λ*(11020) $\bar{b}buds$ J.J.Wu, L.Zhao, B.S.Zou, PLB709(2012)70

From $K\Sigma$, $\bar{K}N \rightarrow \bar{D}\Sigma_c$, $\bar{D}_s\Lambda_c \rightarrow B\Sigma_b$, $B_s\Lambda_b$ bound states

**"Prediction of narrow N* and Λ* resonances with hidden charm above 4 GeV",
Wu, Molina, Oset, Zou, PRL105 (2010) 232001**
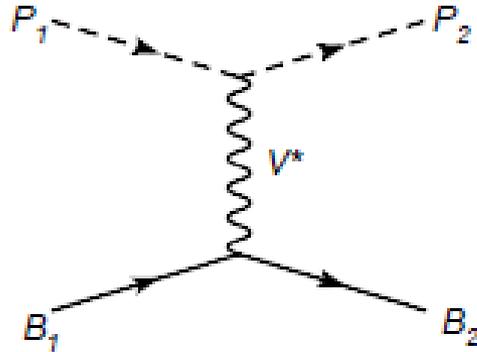
$$\mathcal{L}_{VVV} = ig\langle V^\mu[V^\nu, \partial_\mu V_\nu]\rangle$$

$$\mathcal{L}_{PPV} = -ig\langle V^\mu[P, \partial_\mu P]\rangle$$

$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$V_{ab(P_1 B_1 \rightarrow P_2 B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$

$$V_{ab(V_1 B_1 \rightarrow V_2 B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1 \cdot \vec{\epsilon}_2,$$

$$T = [1 - VG]^{-1}V$$

$$T_{ab} = \frac{g_a g_b}{\sqrt{s} - z_R}$$

N* - $\bar{D}\Sigma_c$

Λ* $\bar{D}\Xi_c$ $\bar{D}\Xi'_c$

J^P

1/2$^-$

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$
	4261	56.9	3.8	8.1	3.9	17.0		23.4
$(0,-1)$			KN	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
	4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8
	4394	43.3	0	10.6	7.1	3.3	5.8	16.3

TABLE V: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $PB \to PB$, with units in MeV.

N*- $\bar{D}^*\Sigma_c$

Λ* $\bar{D}^*\Xi_c$ $\bar{D}^*\Xi'_c$

1/2$^-$, 3/2$^-$

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$
	4412	47.3	3.2	10.4	13.7			19.2
$(0,-1)$			K^*N	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
	4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4
	4544	36.6	0	8.8	9.1	0	5.0	13.8

TABLE VI: Mass (M), total width (Γ), and the partial decay width (Γ_i) for the states from $VB \to VB$ with units in MeV.

Further studies support such hidden charm N*

W.L.Wang, F.Huang, Z.Y.Zhang, B.S.Zou, PRC84(2011)015203:
Chiral quark model → $\bar{D}\Sigma_c$ state ~ 4.31 GeV

Z.C.Yang, Z.F.Sun, J.He, X.Liu, S.L.Zhu, Chin. Phys. C36 (2012) 6
Schoedinger Equation method with $\pi, \eta, \rho, \omega, \sigma$ exchanges
→ $\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ N* state ~ 4.36 – 4.46 GeV

J.J.Wu, T.S.H.Lee, B.S.Zou, PRC85(2012)044002:
EBAC-DCC model → $\bar{D}\Sigma_c$ $(1/2^-)$ ~ 4.3 GeV,
$\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.4 - 4.5 GeV

C.W.Xiao, J.Nieves, E.Oset, PRD 88 (2013) 056012:
Heavy quark spin symmetry → 7 such N* molecules
$\bar{D}\Sigma_c$ $(1/2^-)$ ~ 4.26 GeV, $\bar{D}\Sigma_c^*$ $(3/2^-)$ ~ 4.33 GeV,
$\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.41, 4.42 GeV,
$\bar{D}^*\Sigma_c^*$ $(1/2^-, 3/2^-, 5/2^-)$ ~ 4.48 - 4.49 GeV

M.Karliner, J.L.Rosner, PRL115(2015)122001:
**Pion exchange → $\bar{D}^*\Sigma_c$ $(1/2^-, 3/2^-)$ ~ 4.5 GeV**

S.G.Yuan, K.W.Wei, J.He, H.S.Xu, B.S.Zou, "Study of c̄cqqq five quark system with three kinds of quark-quark hyperfine interaction,"
Eur. Phys. J. A48 (2012) 61

J^P	CM		FS		Inst.	
	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	4494	4541	4253	4156	4360	4272
$\frac{1}{2}^-$	4576		4263		4362	
$\frac{1}{2}^-$	4649		4278		4416	
$\frac{3}{2}^-$	4431	4389	4154	4013	4216	4131
$\frac{3}{2}^-$	4503	4445	4171	4119	4295	4204
$\frac{3}{2}^-$	4549	4476	4263	4136	4362	4272
$\frac{3}{2}^-$	4577	4526	4278	4236	4416	4322
$\frac{3}{2}^-$	4629		4362		4461	
$\frac{5}{2}^-$	4719	4616	4362	4236	4461	4322

J^P	CM		FS		Inst.	
	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^+$	4622	4456	4291	4138	4487	4396
$\frac{1}{2}^+$	4636	4480	4297	4140	4501	4426
$\frac{1}{2}^+$	4645	4557	4363	4238	4520	4426
$\frac{1}{2}^+$	4658	4581	4439	4320	4540	4470
$\frac{1}{2}^+$	4690	4593	4439	4367	4557	4482
$\frac{1}{2}^+$	4696	4632	4467	4377	4587	4490
$\frac{1}{2}^+$	4714	4654	4469	4404	4590	4517
$\frac{1}{2}^+$	4728	4676	4486	4489	4614	4518
$\frac{1}{2}^+$	4737	4714	4492	4508	4616	4549
$\frac{1}{2}^+$	4766	4720	4510	4515	4626	4566
$\frac{3}{2}^+$	4623	4457	4291	4138	4487	4396
$\frac{3}{2}^+$	4638	4515	4297	4140	4501	4426
$\frac{3}{2}^+$	4680	4561	4363	4238	4520	4426
$\frac{3}{2}^+$	4692	4582	4439	4320	4540	4470
$\frac{3}{2}^+$	4695	4625	4439	4367	4557	4482
$\frac{5}{2}^+$	4705	4539	4297	4140	4501	4426
$\frac{5}{2}^+$	4719	4649	4439	4320	4540	4470
$\frac{5}{2}^+$	4773	4689	4467	4367	4587	4482
$\frac{5}{2}^+$	4793	4696	4486	4404	4615	4490
$\frac{5}{2}^+$	4821	4710	4492	4515	4632	4517
$\frac{7}{2}^+$	4945	4841	4638	4508	4698	4566
$\frac{7}{2}^+$	4955	4862	4671	4551	4712	4634
$\frac{7}{2}^+$	4974	4919	4705	4587	4765	4669
$\frac{7}{2}^+$	5010		4759		4797	

**M(5/2⁺) – M(3/2⁻) : 130 ~300 MeV**

Prediction for PANDA
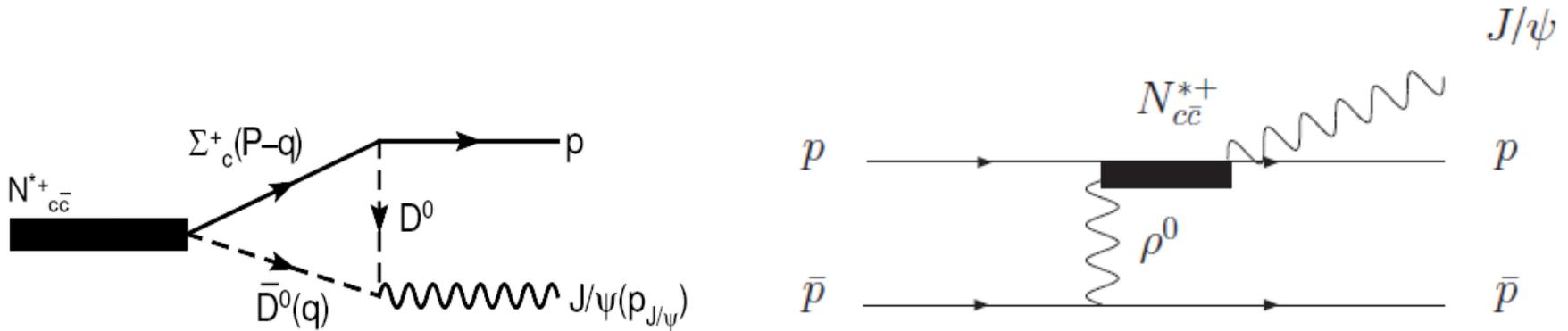
$\bar{p}p \rightarrow \bar{p}pJ/\psi \; > \; 0.1 \; nb$

> 100 events per day at PANDA/FAIR by L=10^{31} cm^{-2}s^{-1}

These Super-heavy narrow N* and Λ* can be found at PANDA !

Albrecht Gillitzer@Juelich had a plan to find them at PANDA

Prediction for 12GeV@JLab
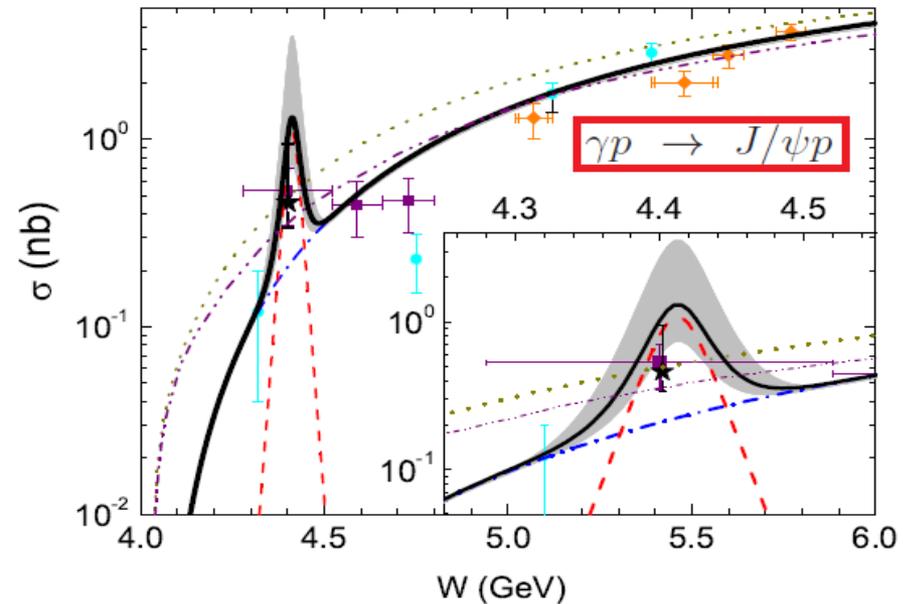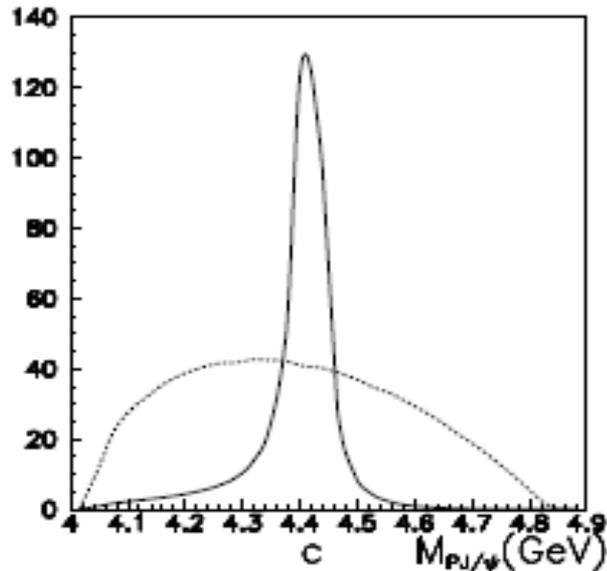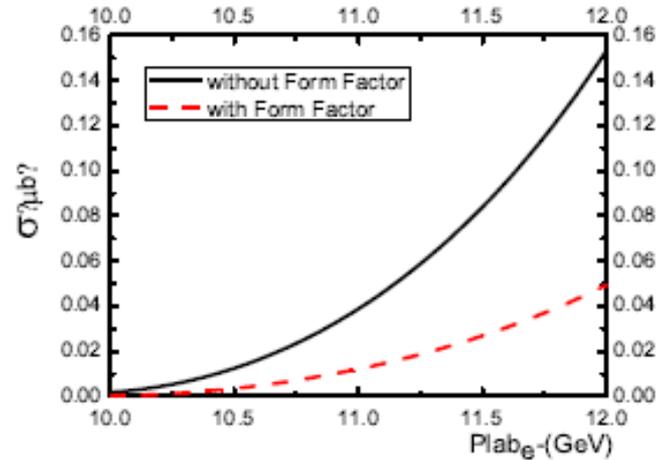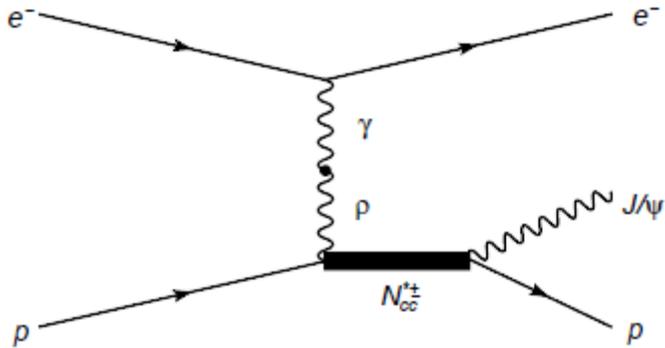
Y. Huang, J.He, H.F.Zhang and X.R.Chen, JPG41, 115004 (2014)

# Proposals for looking for $N_{\bar{c}c}$ & $\Lambda_{\bar{c}c}$ with π^-, K beams at JPARC

a) X.Y.Wang, X.R.Chen, "The production of hidden charm baryon N*(4261) from $\pi^-p \rightarrow \eta_c$ n reaction", EPL109 (2015) 41001.

b) E.J.Garzon, J.J.Xie, "Effects of a $N_{\bar{c}c}$ resonance with hidden charm in the $\pi^-p \rightarrow D^-\Sigma_c^+$ reaction near threshold", PRC 92 (2015) 035201

c) X.Y.Wang, X.R.Chen, "Production of the superheavy baryon Λ*(4209) in kaon-induced reaction", EPJA51 (2015) 85

3. LHCb P_c & P_{cs} states & theory progress

LHCb, Phys.Rev.Lett. 115 (2015) 072001 :
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$
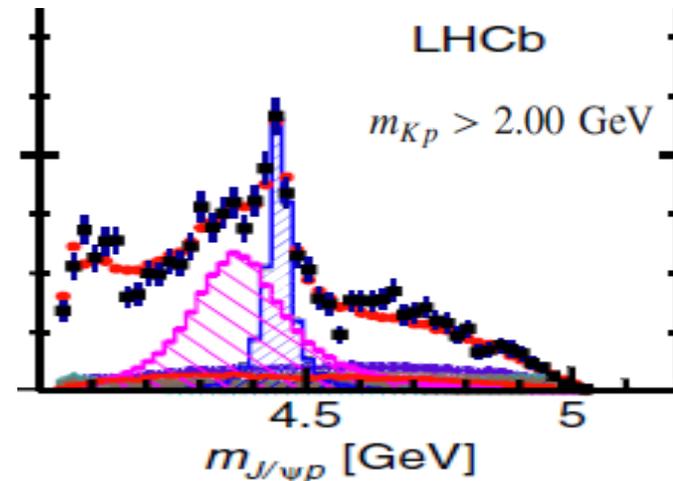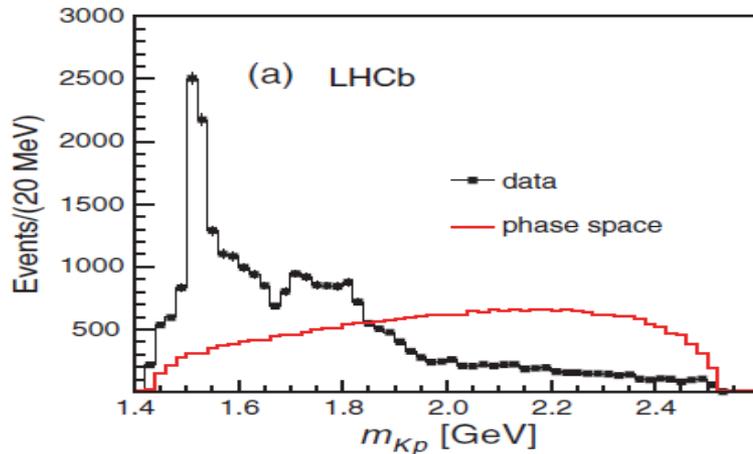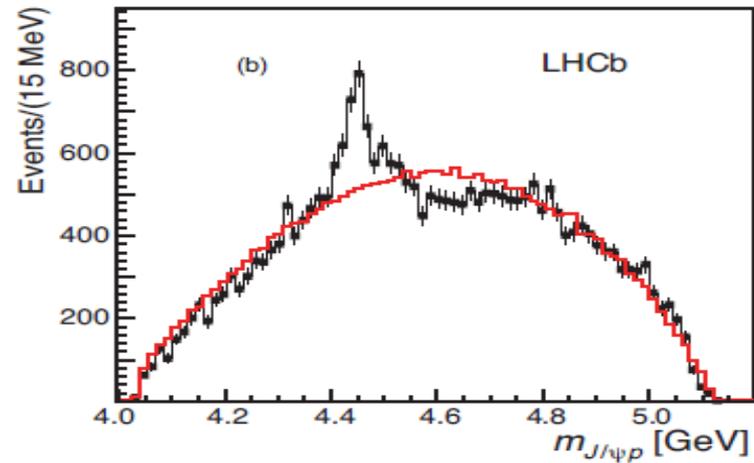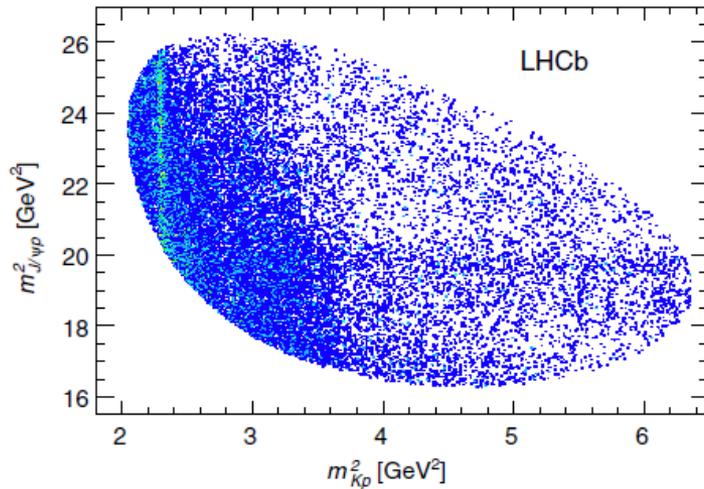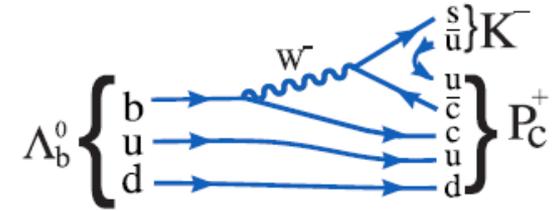
LHCb, Phys.Rev.Lett. 122 (2019) 222001
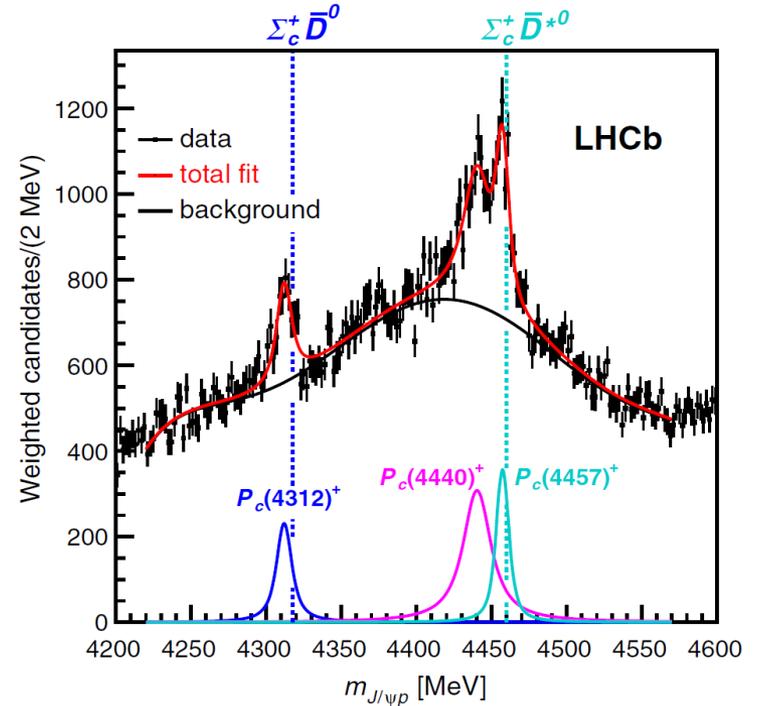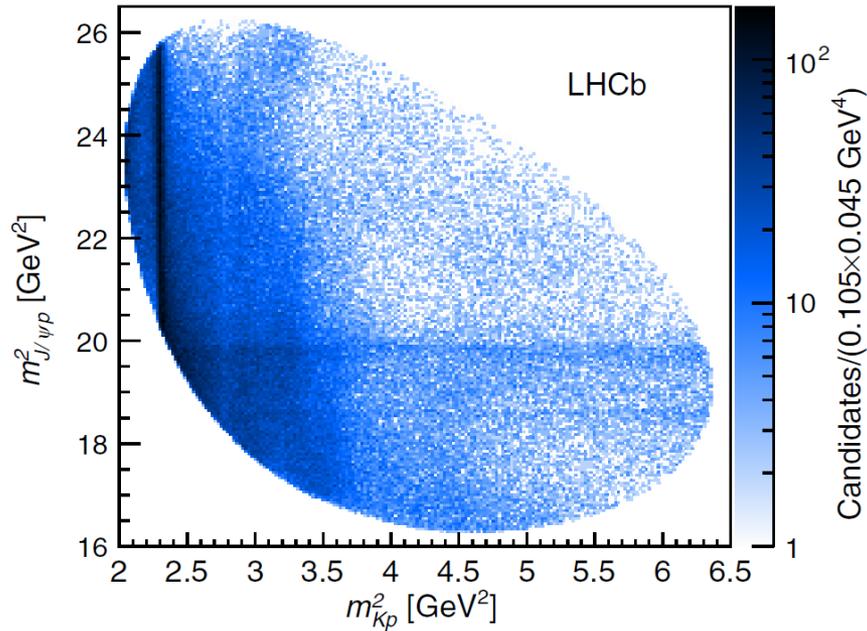
State	M [MeV]	Γ [MeV]	(95% C.L.)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(<20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Comparison to numerical predictions

- Many theoretical predictions for $\Sigma_c^+ \overline{D}^{(*)0}$ published before 2015, **some in quantitative agreement with the LHCb data**

  - Wu,Molina,Oset,Zou, PRL105, 232001 (2010),
  - **Wang,Huang,Zhang,Zou, PR C84, 015203 (2011),**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36, 6 (2012),**
  - **Wu,Lee,Zou, PR C85 044002 (2012),**
  - Karliner,Rosner, PRL 115, 122001 (2015)
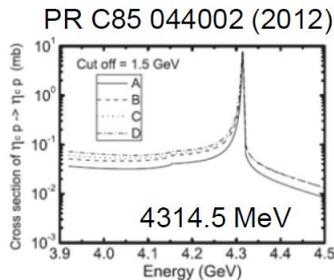
ΔE – binding energy

Example:

Nucleon resonances with hidden charm in coupled-channels models

Jia-Jun Wu, T.-S. H. Lee, and B. S. Zou
Phys. Rev. C **85**, 044002 – Published 17 April 2012

arXiv:1202.1036

TABLE III: The pole position ($M - i\Gamma/2$) and "binding energy" ($\Delta E = E_{thr} - M$) for different cut-off parameter Λ and spin-parity J^P. The threshold E_{thr} is 4320.79 MeV of $D\Sigma_c$ in PB system and 4462.18 MeV of $D^*\Sigma_c$ in VB system. The unit for the listed numbers is MeV.

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	4318.964 − 0.362i	1.826	4459.513 − 0.417i	2.667
	1500	4314.531 − 1.448i	6.259	4454.088 − 1.662i	8.092
	2000	4301.115 − 5.835i	19.68	4438.277 − 7.115i	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	4462.178 − 0.002i	0.002
	1200	-	-	4459.507 − 0.420i	2.673
	1500	-	-	4454.057 − 1.681i	8.123
	2000	-	-	4438.039 − 7.268i	23.14

$\Delta E(4312) = 5.8^{+1.0}_{-6.8}$ MeV

$\Delta E(4457) = 2.5^{+4.3}_{-4.1}$ MeV

$\Delta E(4440) = 19.5^{+4.9}_{-4.3}$ MeV

Λ - cut off on exchanged meson mass.

PR C85 044002 (2012)

4314.5 MeV

$\Xi_b^- \to J/\psi \Lambda K^-$ by LHCb   LHCb-PAPER-2020-039
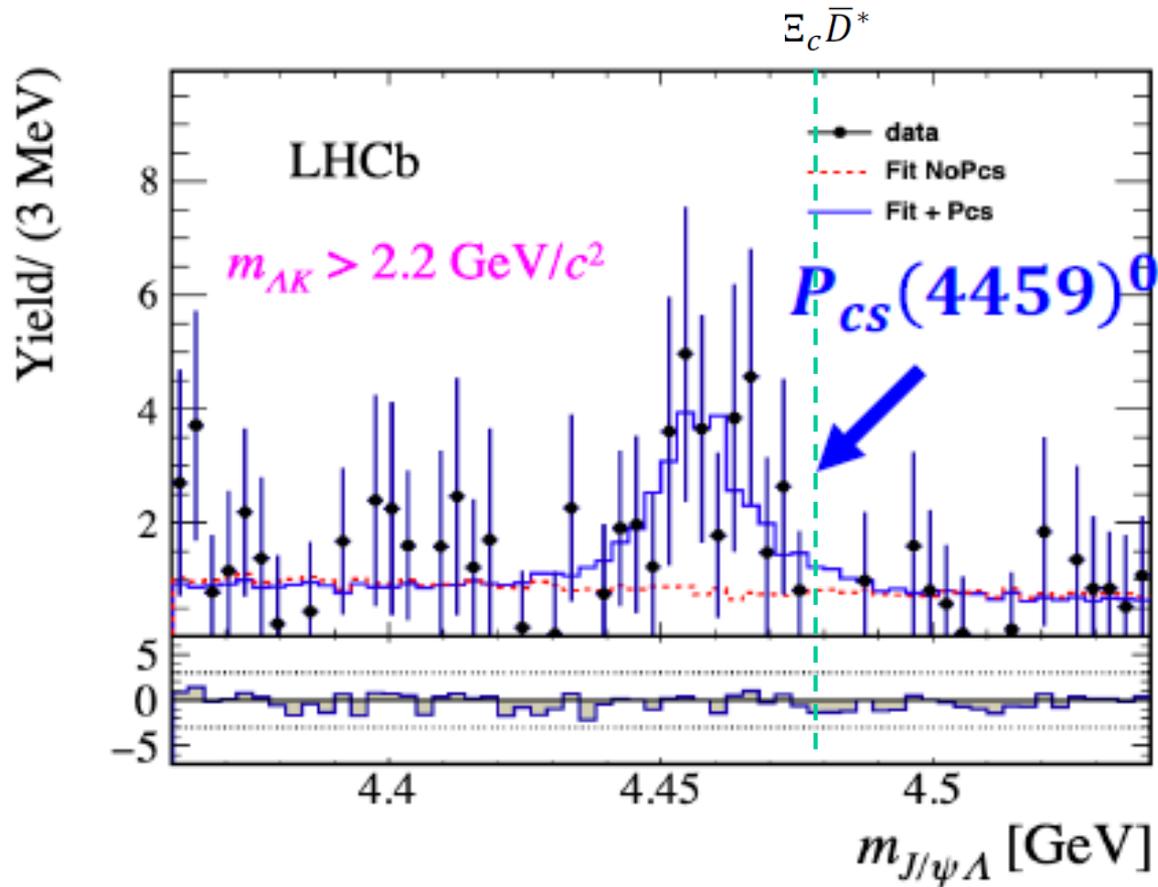
$\overline{D}\Xi_c$ (4337MeV), $\overline{D}^*\Xi_c$ (4478MeV), $\overline{D}\Xi'_c$ (4444MeV), $\overline{D}^*\Xi'_c$ (4585MeV),

$\overline{D}\Xi^*_c$ (4513MeV), $\overline{D}^*\Xi^*_c$ (4654MeV)

Theory progress after LHCb observation of P_c & P_{cs} states

Thresholds $\bar{D}\Sigma_c^*$ **(4383MeV),** $\bar{D}^*\Sigma_c$ **(4460MeV),** $p\chi_{c1}$ **(4449MeV)**

1) $\bar{D}\Sigma_c^*$ **,** $\bar{D}^*\Sigma_c$ **,** $\bar{D}^*\Sigma_c$ ***** **molecular states**

R.Chen, X.Liu, X.Q.Li, S.L.Zhu, PRL115 (2015) 132002;

L.Roca, J.Nieves, E.Oset, PRD92 (2015) 094003;

J.He, PLB 753 (2016)547 ;

2) diquark *cu* **& triquark** $\bar{c}(ud)$ **states**

L.Maiani, A.D.Polosa, V. Riquer, PLB749 (2015) 289;

R.Lebed, PLB749 (2015) 454;

G.N.Li, M.He, X.G.He, JHEP 1512 (2015) 128;

R.Zhu, C.F.Qiao, PLB756 (2016) 259;

3) Kinematic triangle-singularity

F.K.Guo, Ulf-G.Meißner, W.Wang, Z.Yang, PRD92 (2015) 071502

X.H.Liu, Q.Wang, Q.Zhao, PLB757 (2016) 231
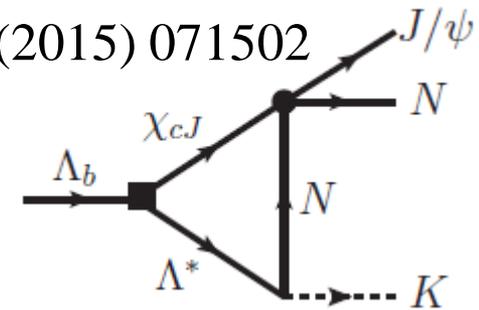
For comprehensive reviews, cf.:
H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1
F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou, RMP 90 (2018)015004
Y.R.Liu, H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Prog.Part.Nucl.Phys. 107 (2019) 237

Multiquark states – crucial for hadron structure !

X(3872)   →   top cited paper for Belle (2003)   1867 cites

Zc(3900)   →   top cited paper for BES (2012)   809 cites

Pc states   →   top cited paper for LHCb (2015)   1114 cites

H.X.Chen, W.Chen, X.Liu, S.L.Zhu, Phys.Rept. 639 (2016) 1:
"The hidden-charm pentaquark and tetraquark states"   613 cites

F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou,
Rev.Mod.Phys. 90 (2018)015004: "Hadronic molecules"   482 cites

Different predictions from various models :

Diquark model by
A.Ali et al., PLB793 (2019) 365

J^P	This work	Refs. [22, 23]
	$S_{ld} = 0,\ L = 0$	
$1/2^-$	3830 ± 34	4086 ± 42
	4150 ± 29	4162 ± 38
$3/2^-$	4240 ± 29	4133 ± 55
	$S_{ld} = 0,\ L = 1$	
$1/2^+$	4030 ± 39	4030 ± 62
	4351 ± 35	4141 ± 44
	4430 ± 35	4217 ± 40
$3/2^+$	4040 ± 39	
	4361 ± 35	
	4440 ± 35	
$5/2^+$	4457 ± 35	4510 ± 57

Hadrocharmonium states by
M.Eides et al., MPLA35(2020)2050151

Constituents	Binding energy [MeV]	Mass [MeV]	Spin-parity
$\eta_c(2S)N$	176.1	4401	$1/2^-$
$\chi_{c1}(1P)N$	44.2	4406	$3/2^+, 1/2^+$
$h_c(1P)N$	43.9	4421	$1/2^+, 3/2^+$
$\chi_{c2}(1P)N$	43.7	4452	$5/2^+, 3/2^+$

Predictions from molecular picture:

$\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ → **7 bound states**

**M.Z.Liu et al., PRL122 (2019) 242001; M.L.Du et al., PRL124 (2020) 072001**
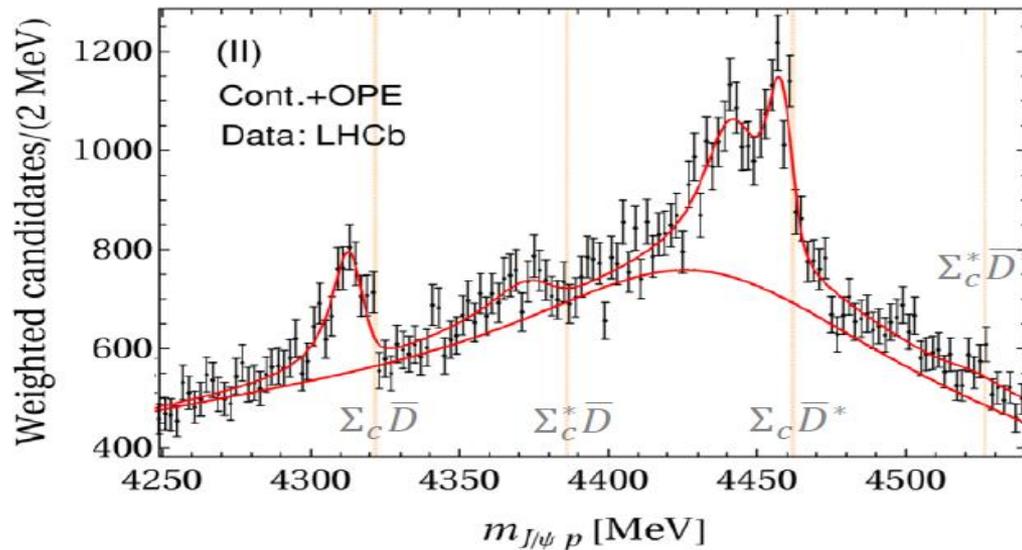
$\bar{D}\Xi_c$ (4337MeV), $\bar{D}^*\Xi_c$ (4478MeV), $\bar{D}\Xi_c'$ (4444MeV), $\bar{D}^*\Xi_c'$ (4585MeV),

$\bar{D}\Xi_c^*$ (4513MeV), $\bar{D}^*\Xi_c^*$ (4654MeV) → **10 bund states**

→ **Different predictions to be checked !**

Disentangling $\bar{D}\Sigma_c^*$ / $\bar{D}^*\Sigma_c$ nature of P_c^+ states from their decays

Y.H.Lin, C.W.Shen, F.K.Guo, B.S.Zou, PRD95(2017)114017
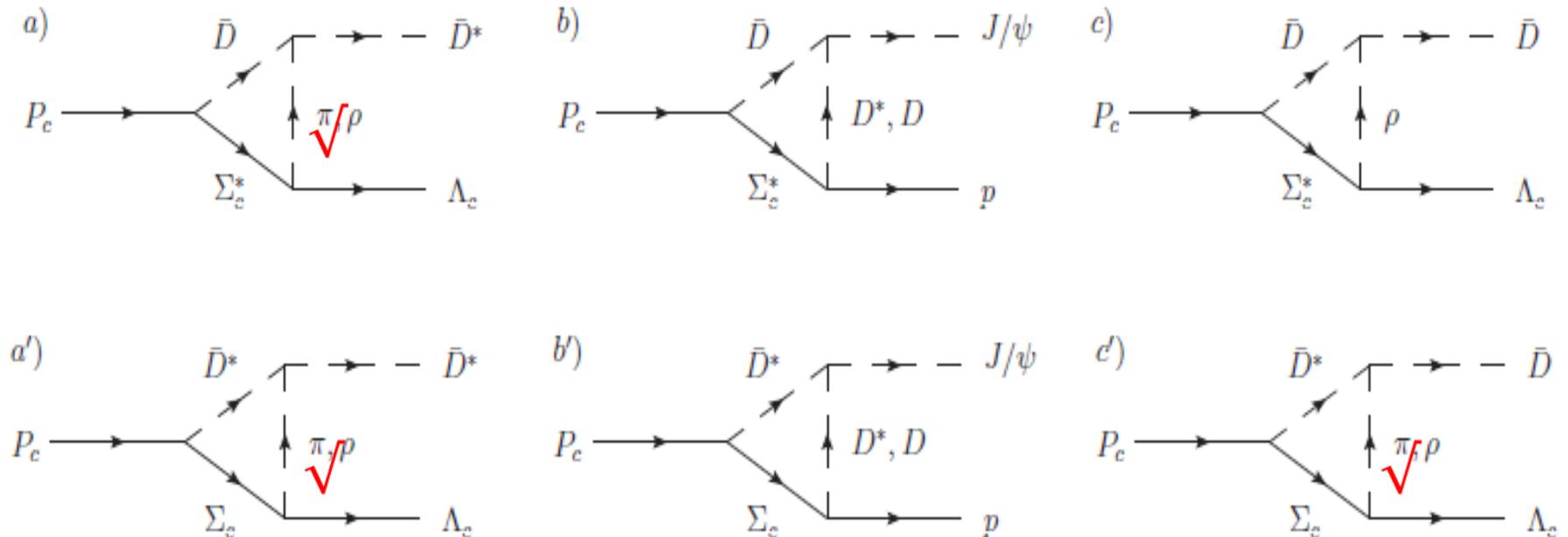
One pion exchange is very important !

$\bar{D}\Sigma_c^*$ & $\bar{D}^*\Sigma_c^*$ are much broader than $\bar{D}\Sigma_c$ & $\bar{D}^*\Sigma_c$ states

# Partial decay widths of $P_c(4312)$, $P_c(4440)$ & $P_c(4457)$

	Widths (MeV) with (f_1, f_3)				
	$\bar{D}\Sigma_c$	$\bar{D}^*\Sigma_c$			
	$P_c(4312)$	$P_c(4440)$		$P_c(4457)$	
Mode	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
$\bar{D}^*\Lambda_c$	3.8	13.9	6.2	12.5	6.1
$J/\psi p$	0.001	0.03	0.02	0.02	0.01
$\bar{D}\Lambda_c$	0.06	5.6	1.7	3.8	1.5
πN	0.004	0.002	~ 0	0.001	~ 0
$\chi_{c0} p$	...	~ 0	~ 0	~ 0	~ 0
$\eta_c p$	0.01	~ 0	~ 0	~ 0	~ 0
ρN	~ 0	~ 0	~ 0	~ 0	~ 0
ωp	~ 0	0.001	~ 0	~ 0	~ 0
$\bar{D}\Sigma_c$	...	3.4	0.5	2.6	1.0
$\bar{D}\Sigma_c^*$	...	0.8	5.4	1.9	6.2
Total	3.9	23.7	13.9	20.7	14.7

It is very important to study $P_c \rightarrow \bar{D}^*\Lambda_c$ & $\bar{D}\Lambda_c$!

Pin down P$_c^+$ states from their photo-production
J.J.Wu, T.S.H.Lee, B.S.Zou, arXiv:1906.05375
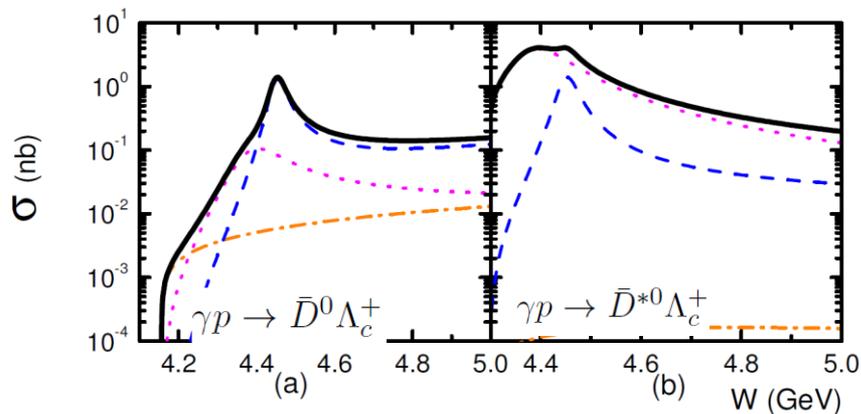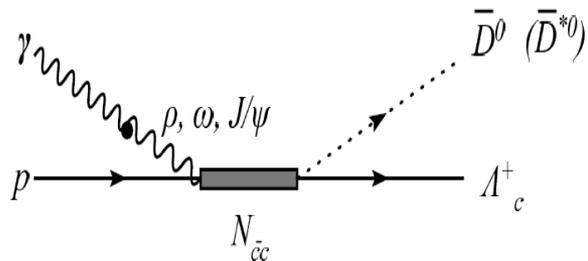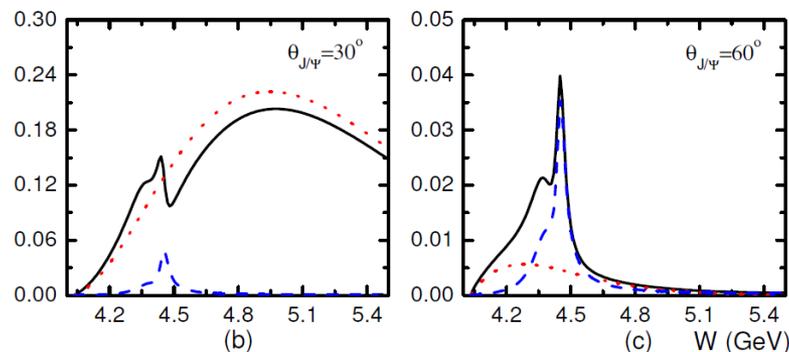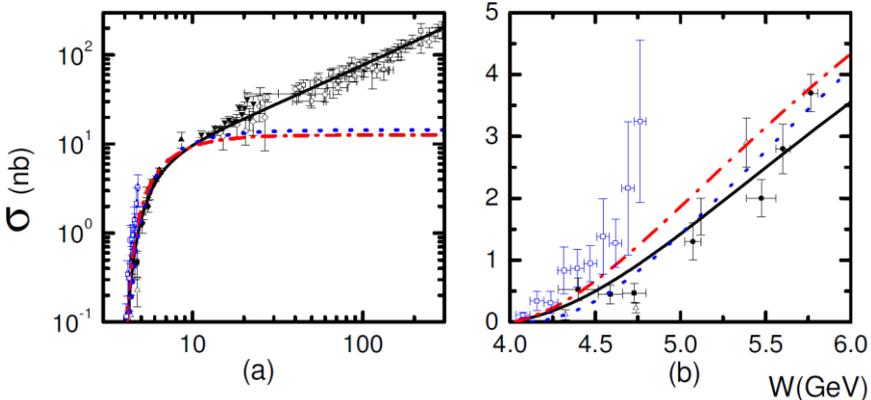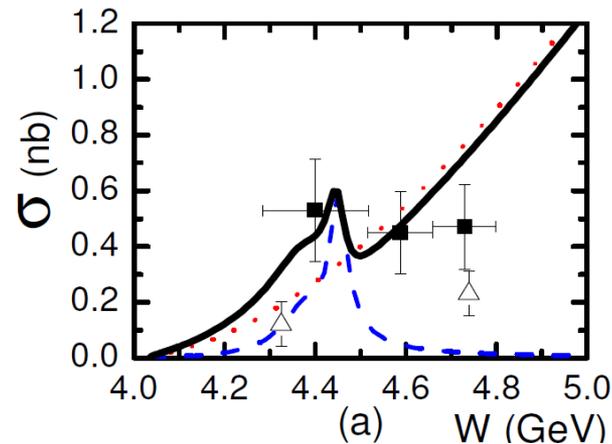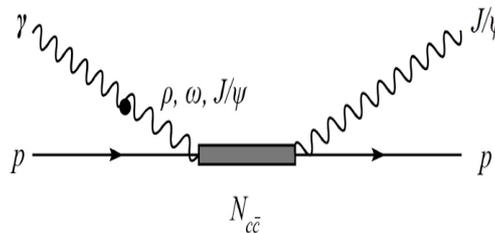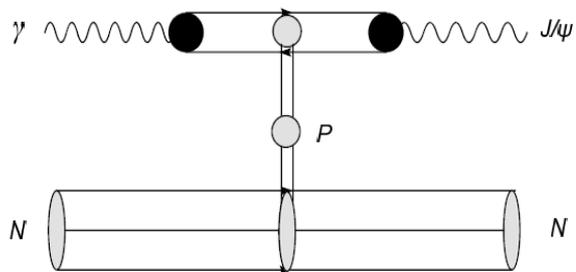
4. Strange & beauty partners of P_c states

Strange partners of P_c and P_{cs} states

$K\Sigma^* \sim 1880$	$K^*\Sigma \sim 2086$	$K^*\Sigma^* \sim 2280$
N*(1875)	N*(2080)	N*(2270)
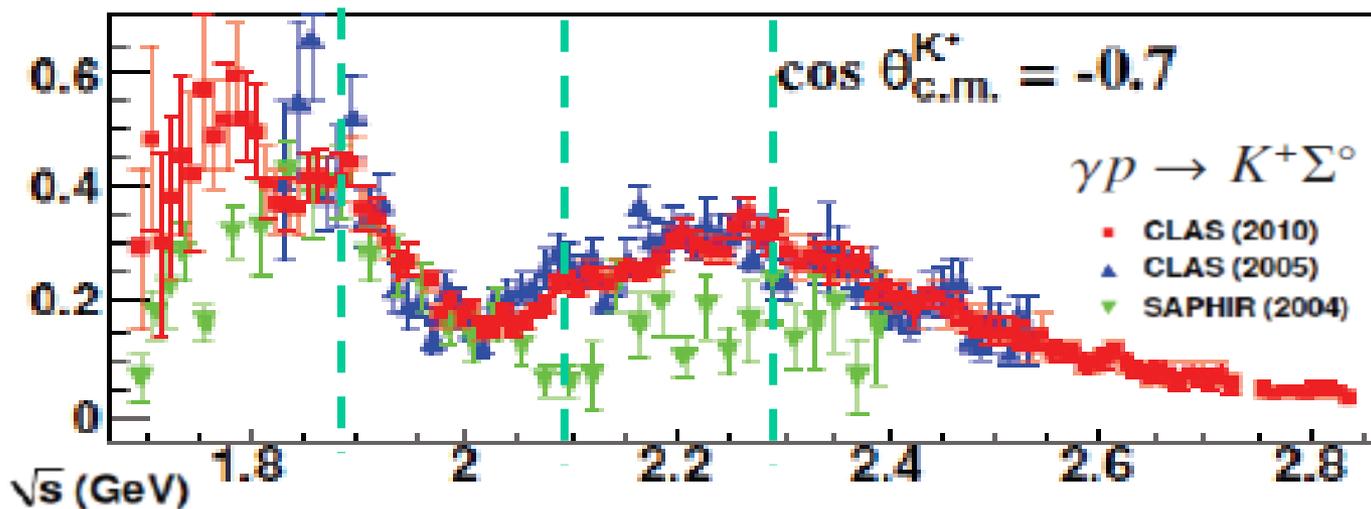
$K\Xi \sim 1810$	$K\Xi^* \sim 2027$	$K^*\Xi \sim 2210$	$K^*\Xi^* \sim 2427$
$\Lambda(1/2^-)$	$\Lambda(3/2^-)$	$\Lambda(1/2^-,3/2^-)$	$\Lambda(1/2^-,3/2^-,5/2^-)$

$K^*N \sim 1833$: $\Lambda(1800)1/2^-$, $\Lambda(3/2^-)$

Strangeness partners of P_c states at BES ?

N*(1875)	N*(2080)	N*(2270)
$K\Sigma^* \sim 1880$	$K^*\Sigma \sim 2086$	$K^*\Sigma^* \sim 2280$
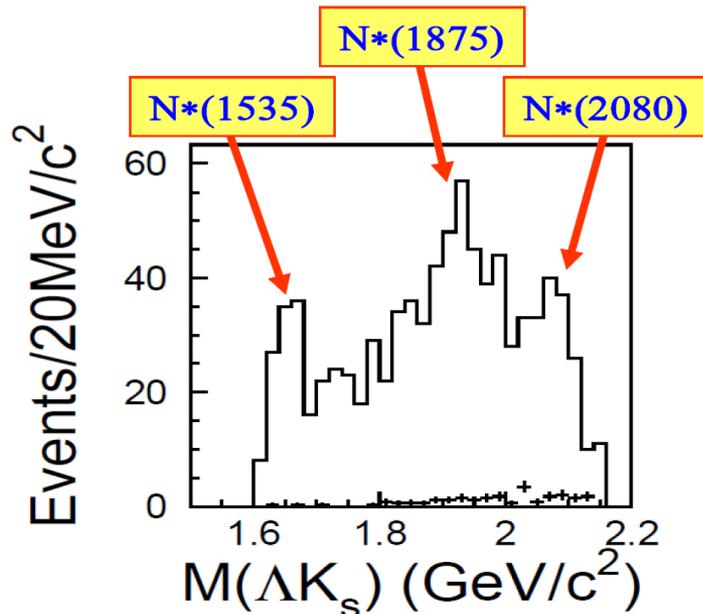
$$J/\psi \to nK_S^0\overline{\Lambda}$$

BESII, PLB659 (2008) 789
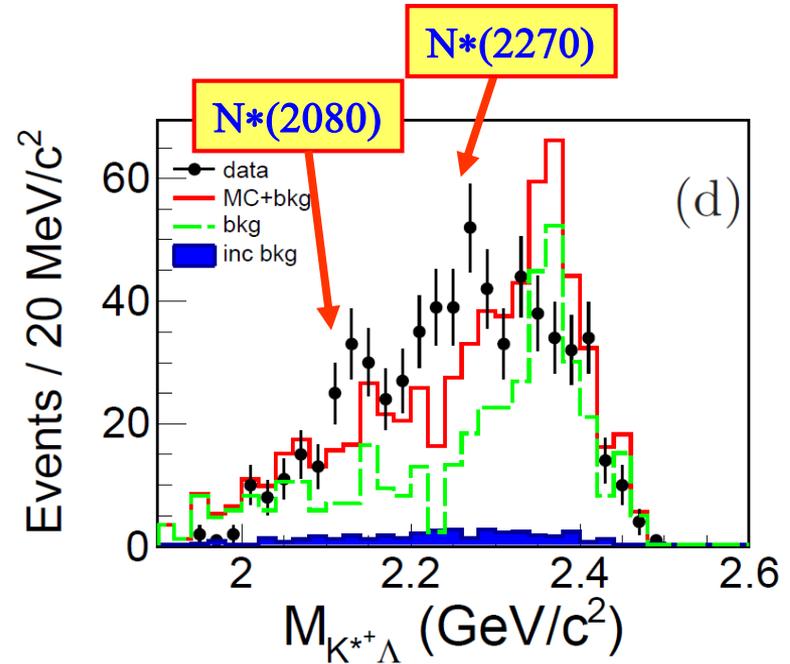
$$\chi_{c0} \to \overline{p}K^{*+}\Lambda + c.c.$$

BESIII, arXiv:1908.02979

Photo-production of pentaquark states with hidden strangeness


$\Lambda_{\bar{s}suds} \rightarrow \Lambda\phi, \Lambda\eta$
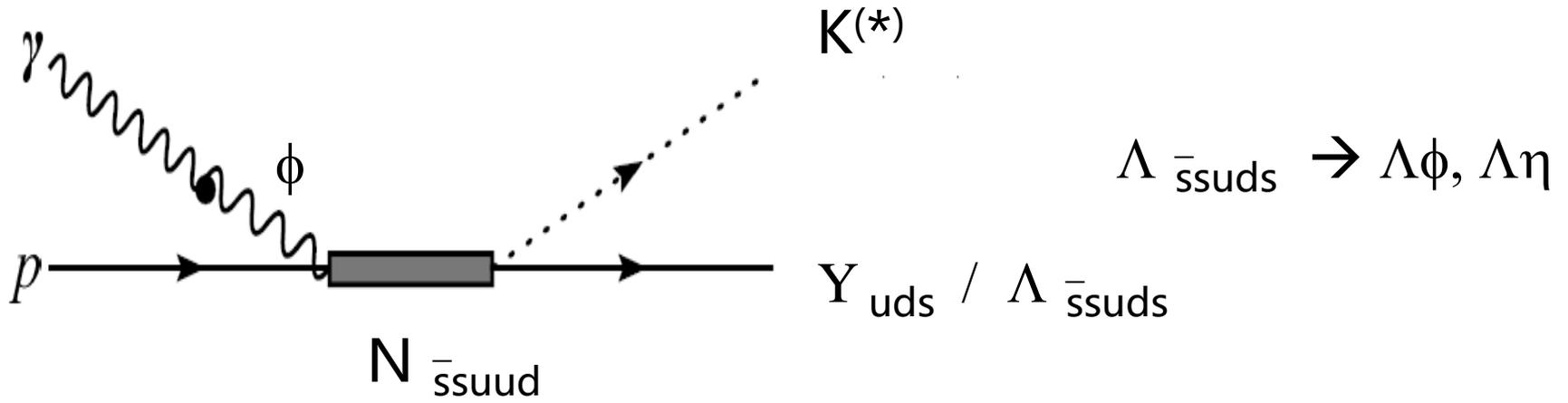
Photo-production of hyperons
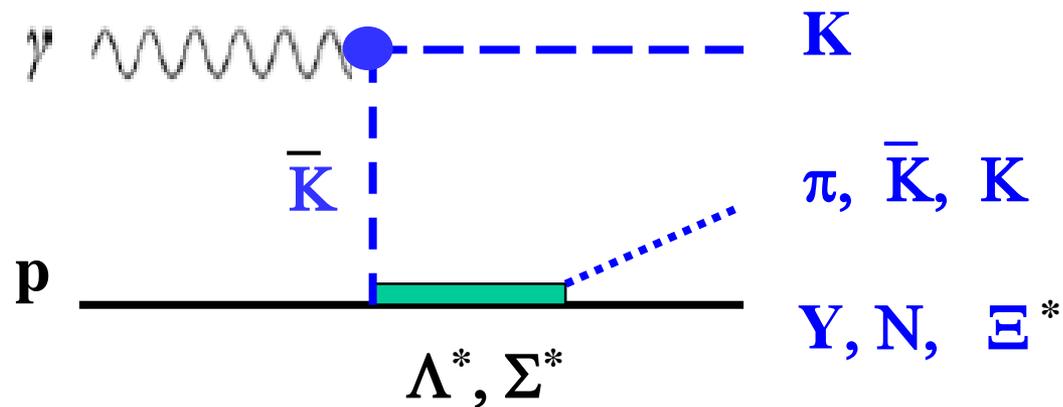
Prediction of super-heavy N^* and Λ^* resonances with hidden beauty

Jia-Jun Wu[a,*], Lu Zhao[a], B.S. Zou[a,b]

| M (MeV)	Γ (MeV)	Γ_i (MeV)					
		πN	ηN	$\eta' N$	$K \Sigma$	$\eta_b N$	
11 052	1.38	0.10	0.21	0.11	0.42	0.52	$1/2^-$
		ρN	ωN	$K^* \Sigma$	ΥN		
11 100	1.33	0.09	0.30	0.39	0.51		$1/2^-,\ 3/2^-$
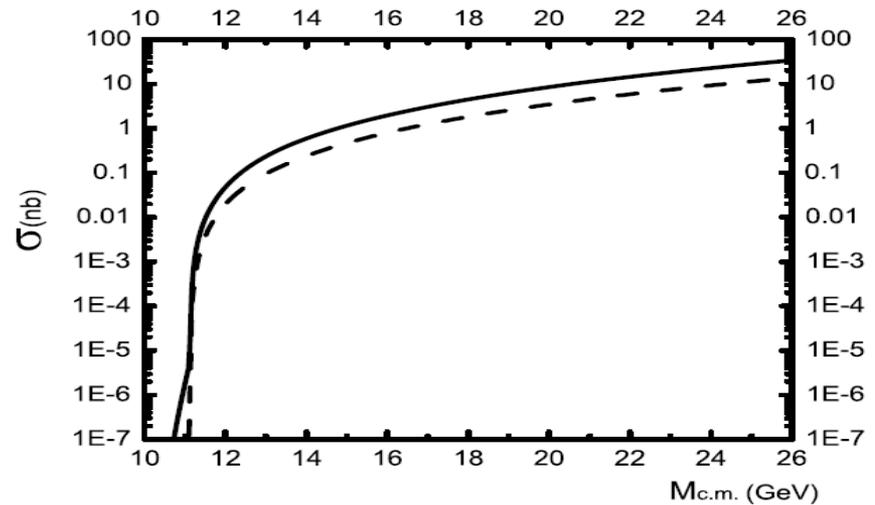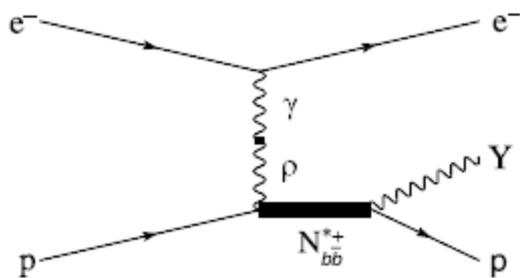
$\bar{D}\Lambda_c - \bar{D}\Sigma_c$ and $B\Lambda_b - B\Sigma_b$ dynamical coupled channel study

C.W.Shen, Roechen, Meissner, Zou, CPC42(2018) 023106
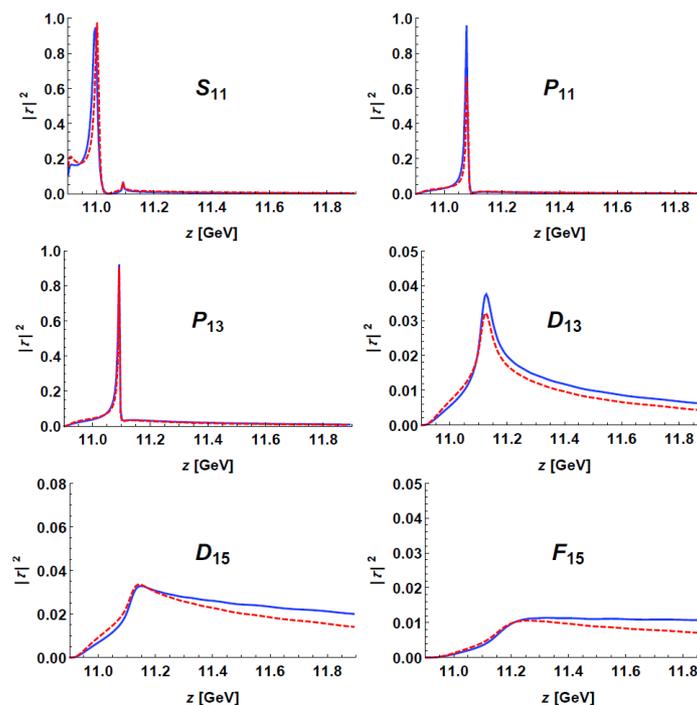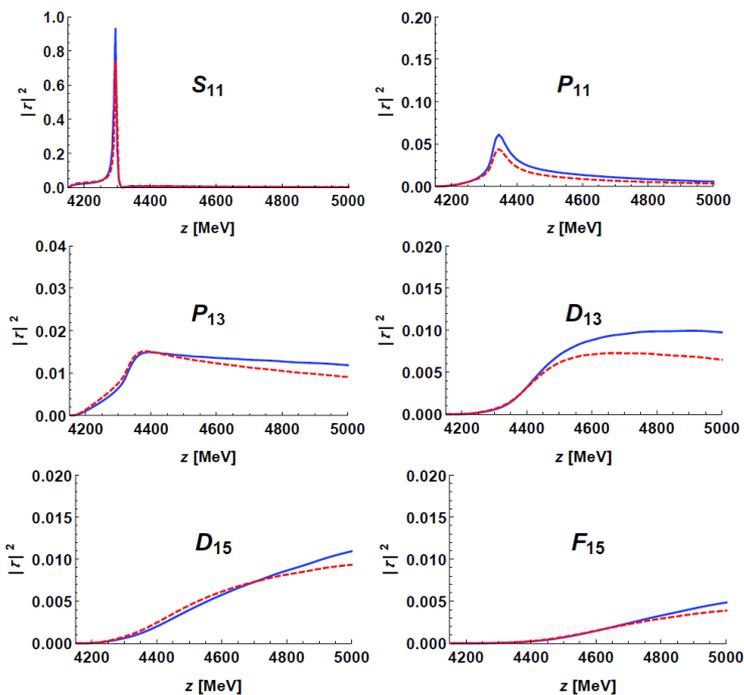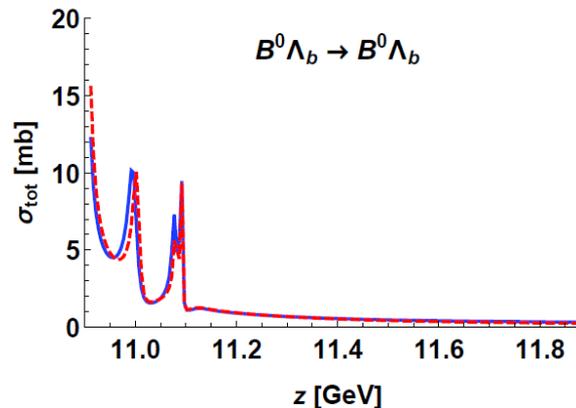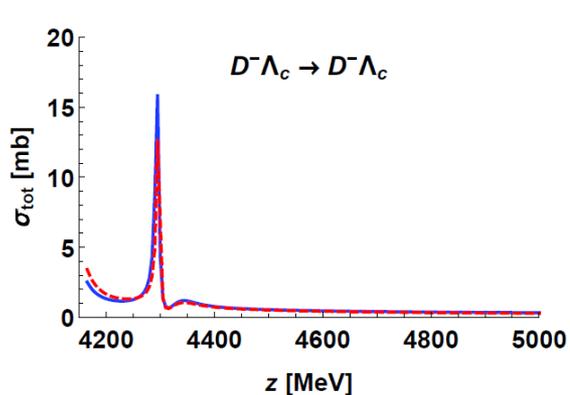
More pentaquarks with hidden beauty than with hidden charm

Decay behavior of P$_s$ & P$_b$ pentaquark states

Mode	Widths (MeV)		
	$J^P = 3/2^-$		$J^P = 1/2^-$
	$N(1875)\, K\Sigma^*$	$N(2080)\, K^*\Sigma$	$N(2080)\, K^*\Sigma$
$N\sigma(500)$	2.6	0.05	0.3
πN	3.8	0.2	22.7
ρN	2.3	3.8	6.1
ωp	6.6	11.3	18.2
$K\Sigma$	0.03	1.4	9.1
$K\Lambda$	0.7	3.7	19.3
ηp	0.6	0.4	1.8
$\pi\Delta$	201.4	82.6	46.9
$K^*\Lambda$	-	2.4	7.9
ϕp	-	19.2	27.0
$K\Sigma^*$	-	7.3	1.3
$K\Lambda(1520)$	-	0.1	1.3
$K\Lambda(1405)$	-	8.0	8.8
$K\pi\Lambda$	10.1	-	-
$K\pi\Sigma$	-	41.3	46.1
Total	228.2	181.7	216.8

Mode	Widths (MeV)		
	$J^P = 3/2^-$		$J^P = 1/2^-$
	$B\Sigma_b^*$	$B^*\Sigma_b$	$B^*\Sigma_b$
$B^*\Lambda_b$	271.1	19.9	167.0
Υp	0.3	0.04	0.1
ρN	5.5	0.02	0.1
ωp	20.9	0.07	0.4
$B\Lambda_b$	-	7.3	135.9
$B\Sigma_b$	-	-	-
$\eta_b p$	0.02	0.0001	0.0009
$\chi_{b0} p$	1.4	0.0008	0.2
πN	0.7	0.005	0.003
$B\Sigma_b^*$	-	-	-
Total	299.9	27.4	303.8

Guidance for P$_s$ & P$_b$ search

Decay behaviors of possible $\Lambda_{c\bar{c}}$ states in hadronic molecule pictures

Guidance for P$_{sc}$ search

5. Prospects

◆ **my favorite strategy for hadron spectroscopy:**

$\overline{c}cuud$ & $\overline{c}cuds$ → sss - $\overline{qq}sss$ → cqq - $\overline{qq}cqq$
→ **hyperons** → **light baryons**

$\overline{c}c\ \overline{u}d$ & $\overline{c}s\ \overline{u}d$ → $\overline{c}c$ - $\overline{qq}\ \overline{c}c$ → $\overline{c}q$ - $\overline{c}q\ \overline{qq}$
→ **K mesons** → **light mesons**

s → c → b
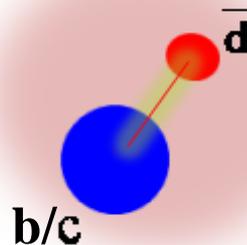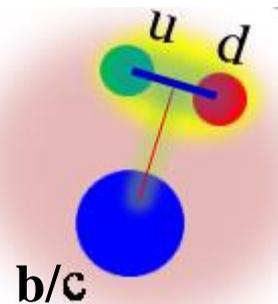
charm & beauty meson   charm & beauty baryon

- **New penta-quark spectroscopy provides a new ideal platform for understanding multiquark dynamics**

- **Further experimental confirmation and extension for whole penta-quark spectroscopy from γN, πN, KN, e⁺e⁻→ $\overline{\Lambda}_b \Lambda_b$, etc.**

  ep/γp@JLab, π10/K10@JPARC, BelleII, BESIII, Eic/EicC, PANDA@FAIR, STCF etc.   may play important role here!

Thank you for your attention!